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ANALYSIS OF A SIMULATED SOURCE OF ELECTROMAGNETIC PULSES.(U)

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ABSTRACT

This thesis describes an effort to develop a source of plane wave electromagnetic pulses for use in an experiment which was designed to measure the electromagnetic field strength across an axial slot in an infinite circular cylinder. Two approaches are described. One design approach attempted to simulate a magnetic line source with an array of small current loops. The second approach attempted to simulate a magnetic line source with an array of long monopoles. It was concluded that a source of plane wave pulses could be constructed, but not without degradation in rise time.

ANALYSIS OF A SIMULATED SOURCE OF ELECTROMAGNETIC PULSES

by

Usto Francis Eugene Schulz

A Thesis Submitted to the Faculty of the

DEPARTMENT OF ELECTRICAL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 0

SO-4T

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I wish to express my appreciation and thanks to Dr. Donald Dudley, whose understanding and help made this project possible. I wish to thank my wife, Bobbie, and my son, Usto, Jr., whose patience and encouragement kept me going. A special thanks to Dr. Manoon Aramrattana for taking time from his own projects to lend assistance. I also want to thank Dr. Reagan, Dr. Wait, and Dr. Schooley for the extra help they provided when the going got rough.

I especially want to acknowledge the United States Air Force for providing the opportunity to pursue this goal.

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS, Continued.

CHAPTER 1

INTRODUCTION

The electromagnetic characteristics of an infinite circular cylinder with an infinite axial slot have been investigated by many workers. Work by Beren (1977) at The University of Arizona considered alternatives to the H Field integral equation, namely the Aperture Field Integral Equation (AFIE) and the E Field Integral Equation (EFIE). Experimental verification of that work was desired.

An experiment was designed to provide empirical data for comparison with the calculated results. An infinitely long cylinder would be simulated by fabricating a 4 feet diameter half-cylinder made from fine wire mesh stretched over a wood frame and mounted on a 28 feet square ground plane. The cylinder design was such that various aperture widths could be accommodated.

However, two potential problem areas were noted in developing the experiment. A technique to measure the field in the aperture without field perturbation was not immediately apparent. The other problem centered on the development of the plane wave source. A single antenna above a ground plane will produce a circular wavefront along the ground plane, as illustrated in Fig. 1.1. Depending on the distance from the source, good approximations of a plane wave can be made. In this experiment, however, the radius is too short. As shown in Fig. 1.1, the wavefront reaches a point 7 feet right of centerline approximately 3

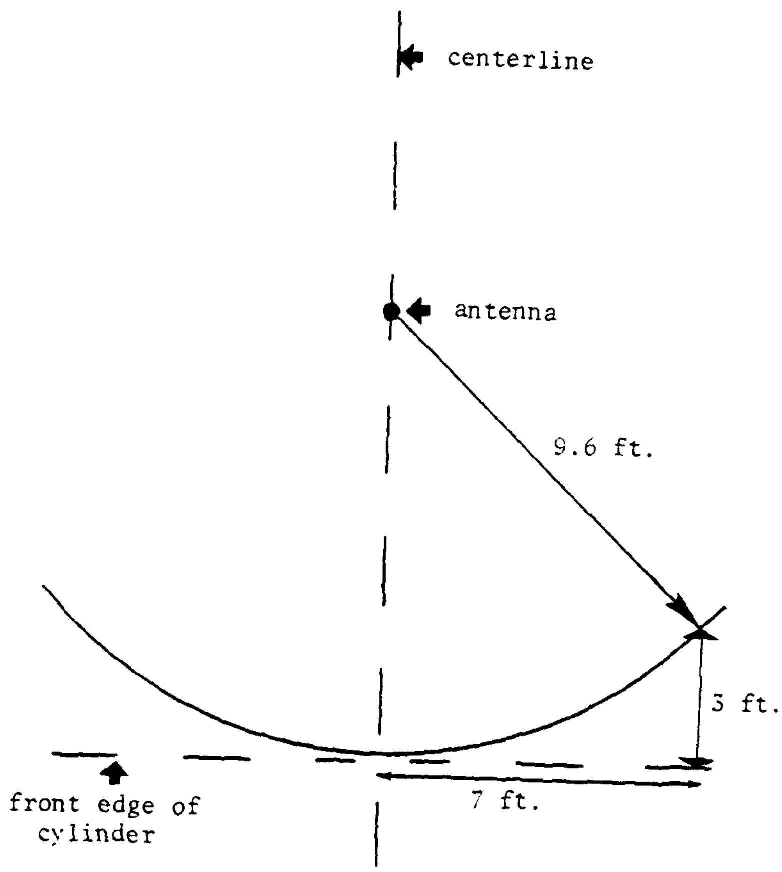
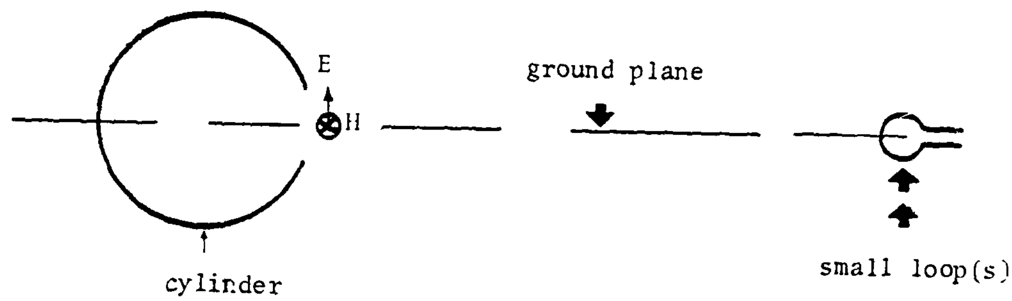


Fig. 1.1. Wavefront produced by single antenna.

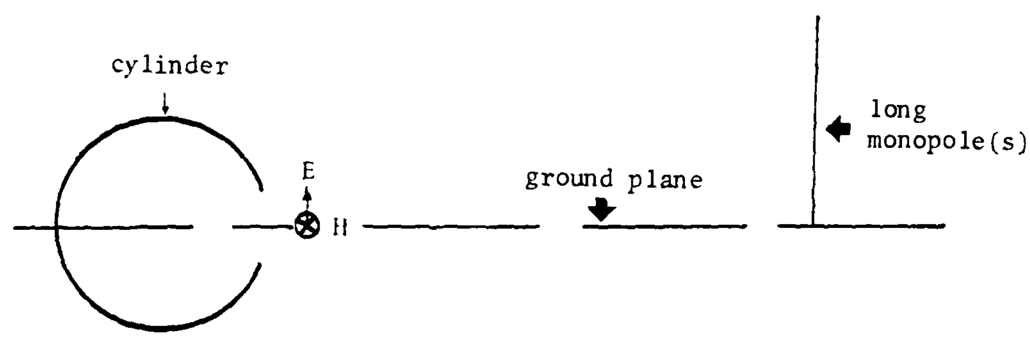
nanoseconds later than the point located on centerline. This time delay produces unacceptable field perturbations for this experiment. The purpose of this thesis is to describe efforts to overcome that problem. The task was to design a source of plane wave pulses which were vertically polarized, had rise times on the order of 0.5 nanoseconds and provided at least 10 nanoseconds of clear time.

Two design approaches were considered. The first approach used an array of electrically small loops with the plane of the loops normal to the ground plane to provide the required vertical polarization (Fig. 1.2a). The second approach used an array of long monopoles with each antenna normal to the ground plane to provide the vertical polarization (Fig. 1.2b). The polarization of the radiated fields of each array were assumed to be equivalent at the cylinder for the purpose of this thesis.

The design, construction and test of each approach are described in subsequent chapters, including a computer simulation of the monopole approach which was developed and verified experimentally to aid in the analysis of that approach. It was found that a source of plane waves could be designed, but not without degradation in pulse rise time.



a. Plane of the loop normal to the ground plane.



b. Monopole normal to the ground plane.

Fig. 1.2. Orientation of the antennas to provide a vertically polarized wave.

CHAPTER 2

THE TEST FACILITY

The Test Facility consists of three basic elements: a ground plane, a system to generate the electromagnetic pulses, and a detection and measuring system. A schematic diagram is shown in Fig. 2.1.

The Ground Plane

The ground plane consists of a 28 feet square wood frame covered with fine wire mesh. Holes were cut for the antenna and probe leads at the points shown in Fig. 2.2. The antennas were spaced along the line designated "line of antennas", and measurements of the radiated fields were taken at the points shown. Throughout this paper, where symmetry is discussed, it is with respect to a line dividing the ground plane in half, and is designated the "centerline" in Fig. 2.2 and subsequent figures.

Pulse Generator

The pulses for this experiment are provided by a Tektronix 109 Pulse Generator using an external power supply. The pulses have a nominal 0.5 nanosecond rise time and nominal 200 volt peak amplitude at the input to the E-H Research 1:100 tee which is used to provide a trigger pulse for the sampling oscilloscope, as well as a reference pulse for comparison purposes.

The array elements are connected using power dividers and 10 nanosecond low-loss coaxial cables. The insertion loss between any two

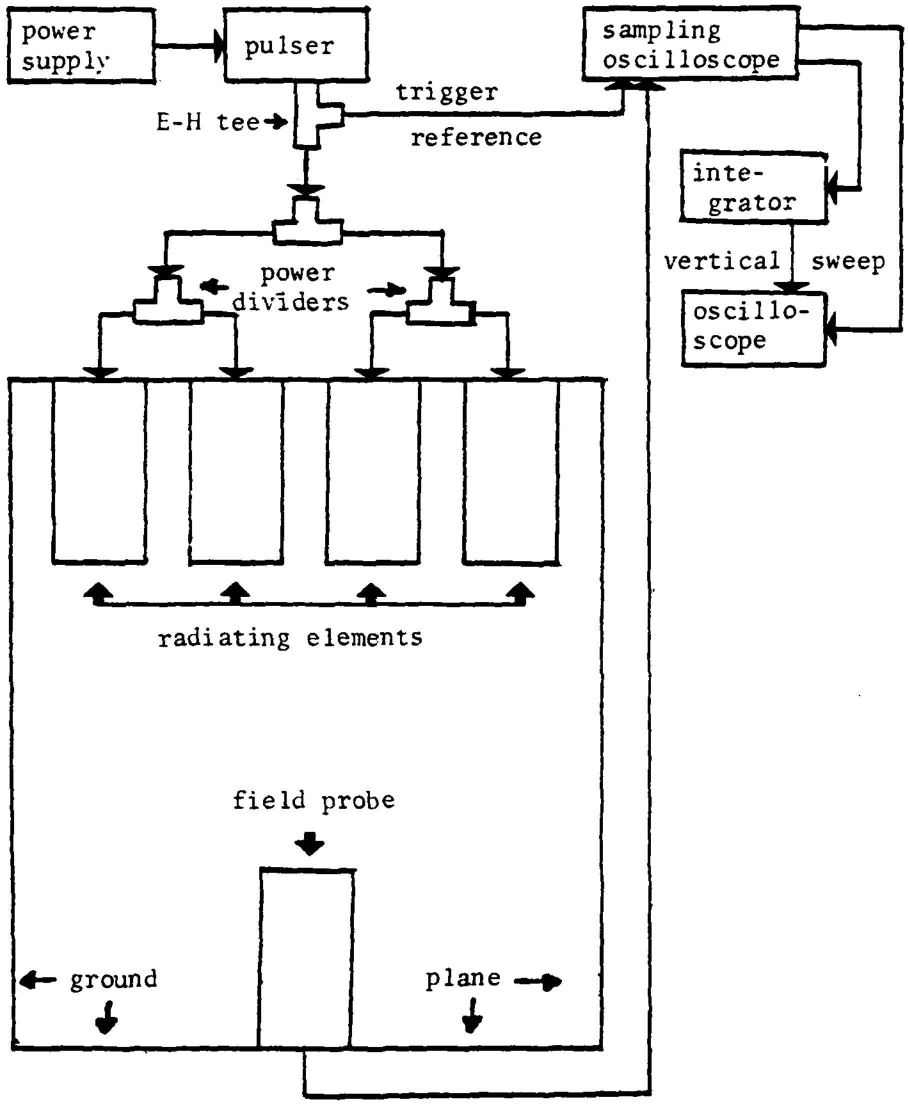


Fig. 2.1. Test facility schematic.

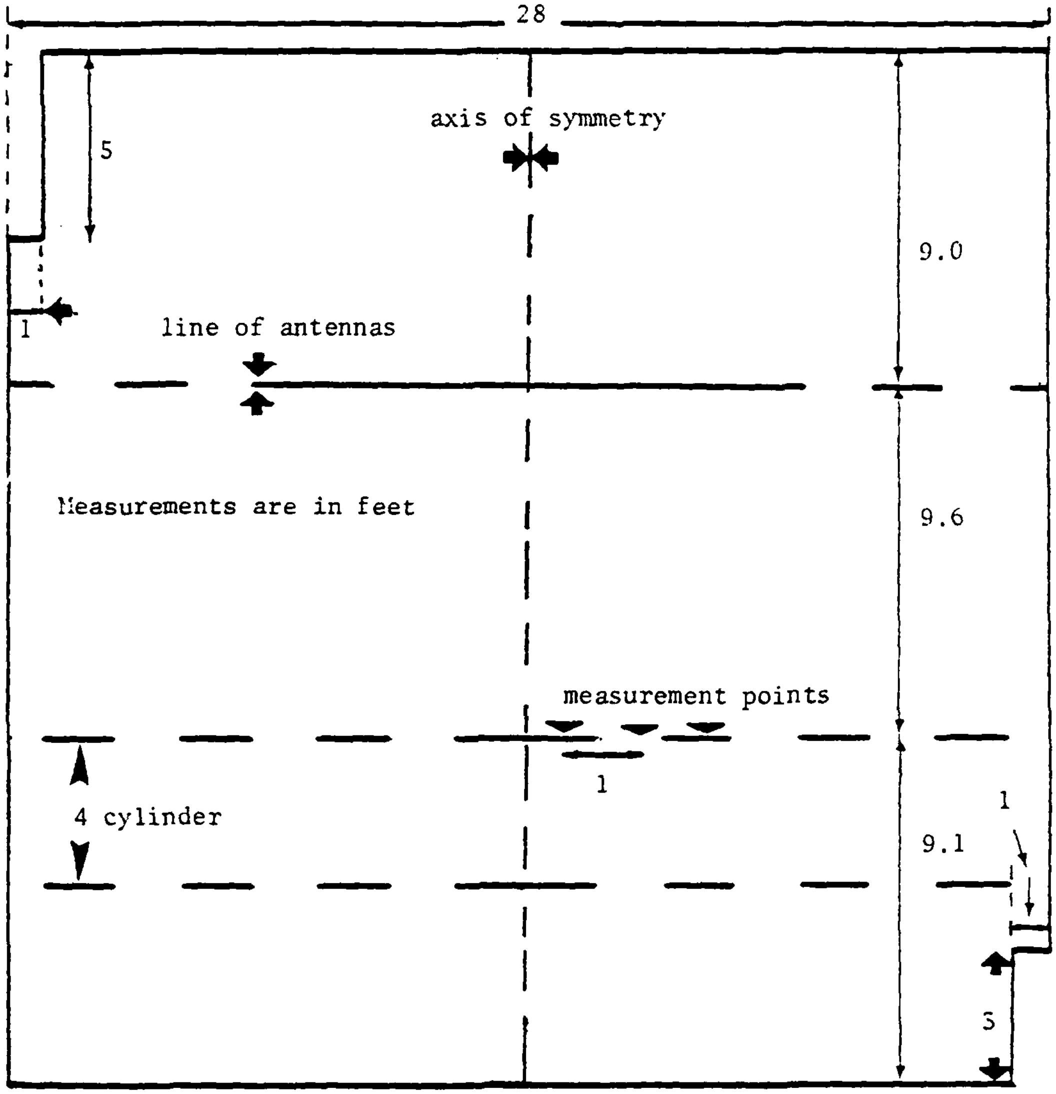


Fig. 2.2. Ground plane.

ports, when the third port is connected to a matched termination, is nominally 6 dB (General Radio, 1972). The 10 nanosecond cables allow a clear time of 20 nanoseconds before mismatch reflections are noted. Holes were cut through the groundplane to allow the antennas to be connected. However, the antenna baseplates were of sufficient size to provide a continuous conducting surface.

Detection and Measurement System

Field probes were constructed to detect the radiated fields. A small half-circular loop probe was constructed using RG-174 coaxial cable, a connector, and a small brass baseplate as described in Appendix B, Fig. B.1. Several iterations were required to construct a similar monopole probe with the desired response, a 3 inch 220 ohm base loaded monopole using RG-174 coaxial cable, a connector and a small brass baseplate. This will be discussed in more detail later.

A Tektronix Sampling Oscilloscope was used to display system response. Using the dual trace feature, it was possible to compare the system response to a reference pulse. The single sweep feature proved useful in recording the data. The vertical output of the unit could be connected to an integrator for additional processing when desired. The results of the integration were displayed on a standard HP 130B oscilloscope. The sampling oscilloscope sweep was used to drive the HP 130B sweep, both being calibrated and synchornized. A complete list of equipment is contained in Appendix A.

System Operation

To test the system operation, an initial check was made using an existing 8 feet monopole as the transmitting antenna, a square wave input pulse, and a short monopole probe as the receiving antenna. The test was based on a paper published in 1966 by Schmitt, Harrison, and Williams which showed that a long monopole antenna transmits a replica of the input voltage. This conclusion was obtained from the following expression for the radiated field, E(f):

$$E(f) = j\,\frac{k}{2\pi}\left[\frac{V_g(f)}{Z_o(f) + Z_g(f)}\right]\left[\frac{e^{-j\beta\gamma}}{r}\right]\beta h_e(f) \qquad (2.1)$$

where

k = characteristic resistance of space

β = radian wave number

V_g = input voltage

Z_g = input source impedance

Z_o = antenna impedance

h_e = effective height of antenna

When the above equation was transformed and numerically integrated, the comparison of calculated and experimental results was excellent (Schmitt et al., 1966). The paper also showed that the load voltage of a short monopole probe in reception was proportional to the derivative of the incident field. The expression for the load voltage, V_L, obtained from the paper, is shown below:

$$V_L(f) \doteq -j2\pi\ f \left[\frac{2\pi h^2 Z_L}{c\ k}\right] E^{inc}\ (f) \tag{2.2}$$

where

h = height of antenna

Z_L = load impedance

c = speed of light

k = characteristic resistance of space

E^{inc} = incident field

When Eq. (2.2) is transformed, the derivative relationship in the time domain is shown. Comparison of the calculated and experimental results again showed excellent agreement (Schmitt et al., 1966). Thus, it is concluded that the load voltage of a short monopole probe in response to the field radiated by a long monopole is proportional to the first derivative of the input voltage. Figure 2.3b shows the predicted response of a short monopole probe to the field radiated by a long monopole excited by the voltage pulse shown in Fig. 2.3a.

In the initial system check using the equipment just described, a 5 nanosecond pulse was input to the antenna. The probe response to the radiated field shown in Fig. 2.4 was assumed to be distorted by ringing. To eliminate the ringing, various tests were performed using resistors to base load the probe. Values of resistance from 120 ohms up to 330 ohms were tested, and 220 was selected as providing the optimum result. Figure 2.5 shows the load voltage response measured from a 3 inch probe (upper photo) and the subsequent integration of that pulse (lower photo) when a long monopole was excited by the 5 nanosecond square wave pulse. These results constituted a successful check of the system.

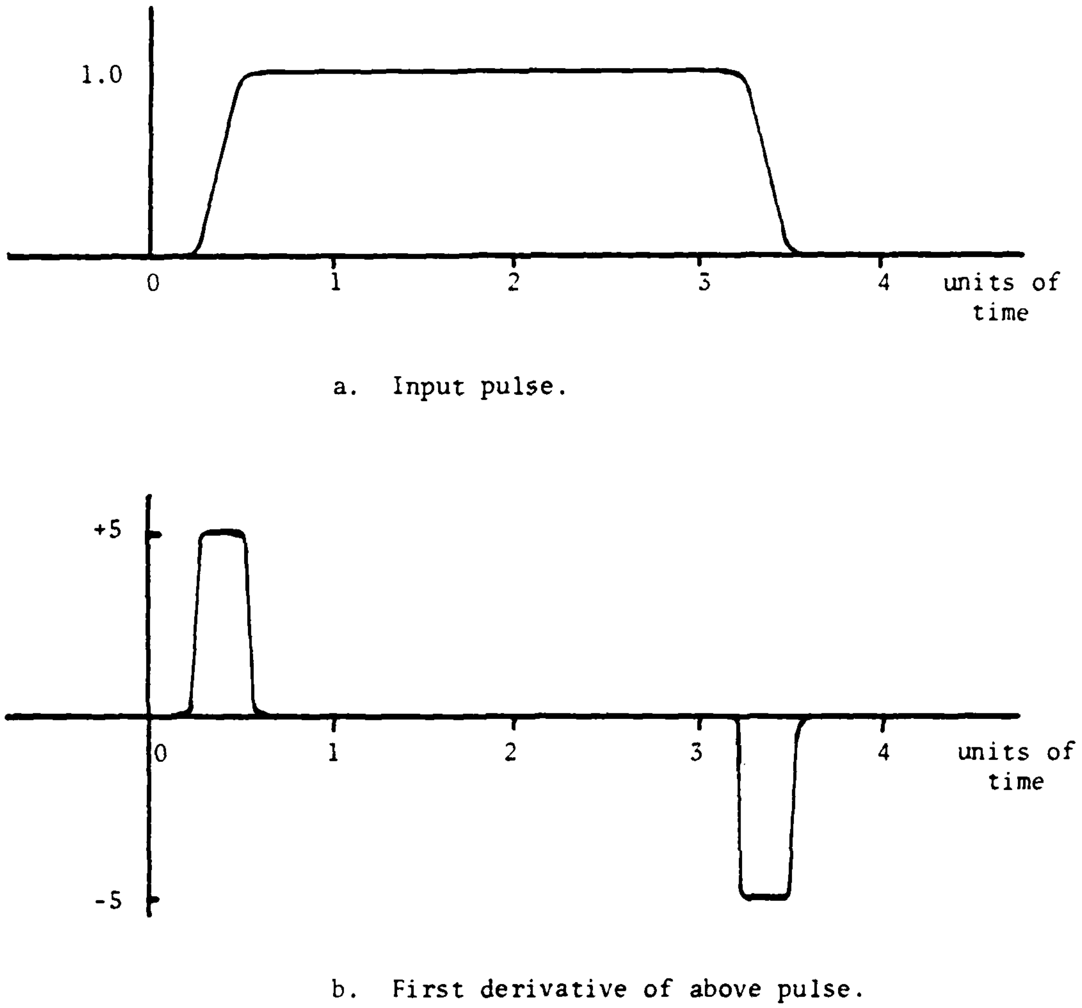
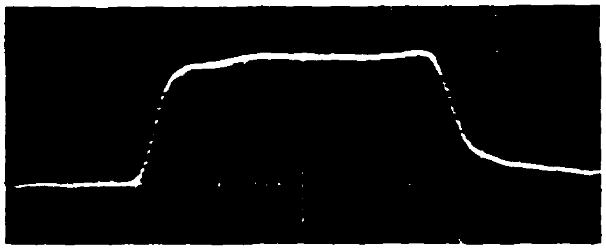


Fig. 2.3. Graphic representation of a pulse with finite rise time and its first derivative.

vertical:

100mV/cm



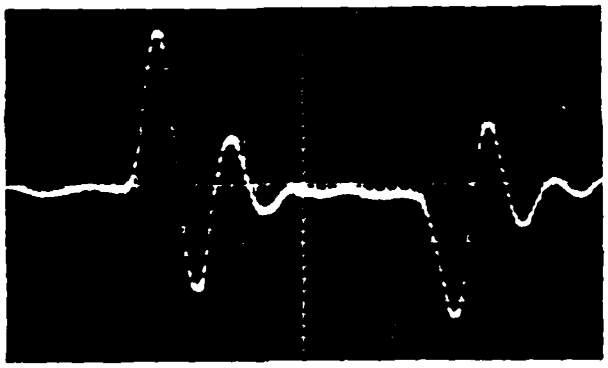
horizontal:

1 Nsec/cm

a. Input voltage waveform to 8 ft. monopole antenna (measured from E-H tee)

vertical:

50mV/cm



horizontal:

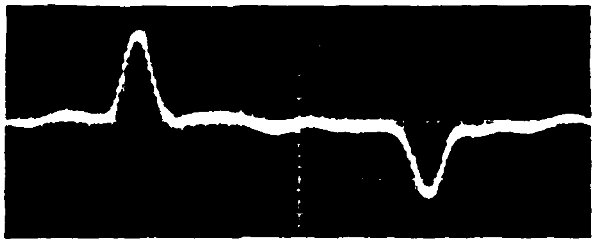
1 Nsec/cm

b. Load voltage response of 3 inch monopole probe to field radiated by 8 ft. monopole excited by square pulse input voltage (above).

Fig. 2.4. Results of initial system checkout.

vertical:

50mV/cm



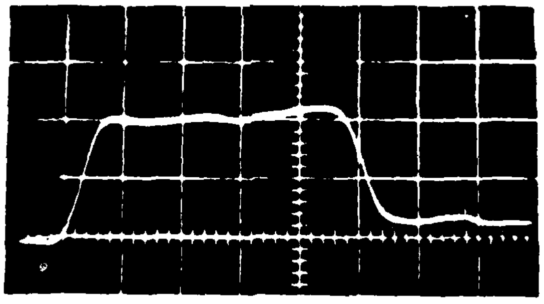
horizontal:

1 Nsec/cm

a. Load voltage response of 3 inch monopole probe, 220 ohm base loaded, to field radiated by 8 ft. monopole excited by square wave input voltage pulse.

vertical:

50mV/cm



horizontal:

1 Nsec/cm

b. Above probe response integrated once.

Fig. 2.5. Initial system checkout using base loaded (220 ohm) field probe.

Frequency Content of the Pulses

Studies have shown that the upper limit of the spectrum of a pulse and its rise time are inversely proportional (E-H Research Laboratories, 1963). The pulses provided by the Tektronix pulser were consistently measured at 0.6 nanoseconds. Using the following relationships (E-H Research, 1963):

$$\text{Observed Rise Time} = \sqrt{S^2 + P^2} \tag{2.3}$$

where

S = oscilloscope rise time,

P = pulse rise time,

and

$$F = \frac{.35}{P} \tag{2.4}$$

where

F = frequency in Hertz

P = rise time in seconds

the high frequency content of the pulses was calculated to be 783 MHz.

CHAPTER 3

SIMULATION OF THE RADIATED FIELD OF AN ARRAY OF LONG MONOPOLES

Two approaches to the design of the plane wave source previously described will be discussed. The first approach centers on the simulation of a magnetic line source using an array of electrically small loops. The antenna design and theory will be discussed briefly, followed by a description of the experimental results. The second approach centers on using an array of long monopoles for which a computer simulation was developed and verified experimentally. The results obtained from that simulation provide the basis for the conclusions of this paper.

Simulating a Magnetic Line Source

Four electrically small half-cylinder loop antennas with 6 inch diameters were fabricated for this experiment. See Appendix B for design criteria. A paper published by Franceschetti and Pappas (1974) showed that the radiated field, E(t), from a small loop antenna could be expressed by:

$$E(t) = k \frac{\dot{v}(t^*)\ A}{4\pi r c^2\ L} \tag{3.1}$$

where

k = characteristic resistance of space

$\dot{v}$ = input voltage--(the dot (·) indicates the derivative with respect to time)

t^* = retarded time (t-r/c)

r = distance from source to probe

c = speed of light

A = area of loop

L = static inductance of the loop

Thus the radiated field of a small loop antenna is proportional to the first derivative of the input voltage. Harrison (1964) had previously shown that the load voltage, V_L, of a small loop antenna in reception, which in the frequency domain can be expressed by:

$$V_L = \frac{-jwA}{k} \frac{Z_L(f)}{Z_o(f) + Z_L(f)} E^{inc}(f) \qquad (3.2)$$

where

k = characteristic resistance of space

A = area of loop

Z_L = load impedance

Z_o = source impedance

$E^{inc}(f)$ = incident field

was proportional to the first derivative of the incident field. Thus, from Eqs. (3.1) and (3.2), it was concluded that the load voltage of a small loop probe in response to the field radiated by a small loop antenna excited by a square wave pulse is proportional to the second derivative of the input voltage, as illustrated in Fig. 3.1. However, when a single small loop was actually used to radiate to a small probe, the load voltage actually measured was considerably distorted (Fig. 3.2b). The distortion was assumed to be caused by ringing. Loading of the antennas

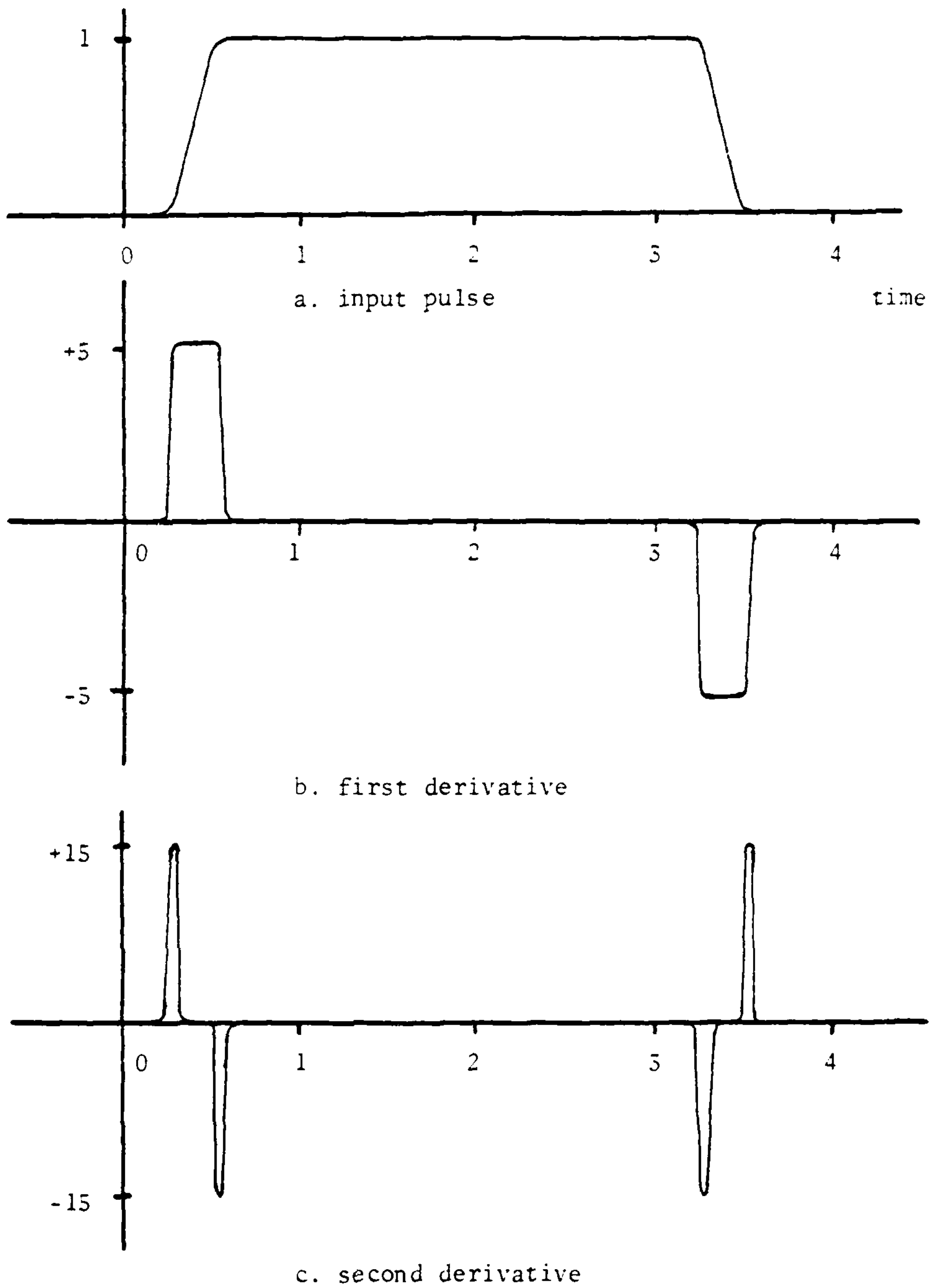
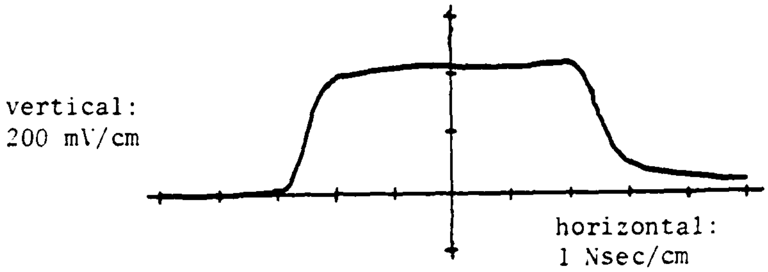
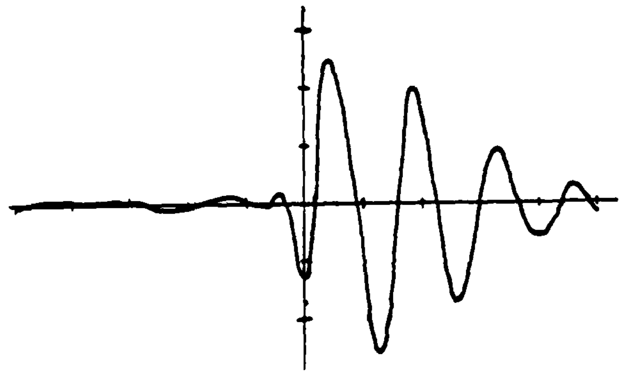


Fig. 3.1. Graphic representation of first and second derivative of a pulse with finite rise time.



a. Input voltage measured from E-H tee



b. Load voltage of small loop probe on centerline, small loop antenna excited by square wave pulse with finite rise time

Fig. 3.2. Results of initial test using single small loop antenna and small loop probe.

to eliminate the ringing was considered, as in the case of the monopoles previously described. However, because of the derivative nature of the voltages both in transmission and reception, analysis was expected to be considerably more difficult. As a result, the loop approach was set aside, and an approach using an array of monopoles based on the work performed during the system check was developed.

Analysis of an Array of Long Monopoles

It was previously shown that a single long monopole radiates a replica of the input voltage. Analysis of the array was begun using a two-element array, and evolving to larger arrays. As shown in Fig. 3.3, the distance from both antennas to any point along the centerline are equal. This implies that pulses will arrive simultaneously at points along the centerline, and have a shape identical to that radiated by a single antenna. For points away from centerline, the distances from each antenna to the point are not equal, which implies that the pulses will not arrive at the point simultaneously and the shape will not be identical to that of a single antenna. For example, if a two-element array of monopoles were excited with an ideal square wave pulse, the radiated field along the centerline would be a square wave pulse. However, for points off centerline, a "stair-step" effect would be expected as illustrated in Fig. 3.4. For arrays of more than two elements, the stair-step effect will always occur because no more than two elements will be equidistant. Figure 3.5 shows a four-element array with the point on centerline, while Fig. 3.6 shows the same array with the point off centerline.

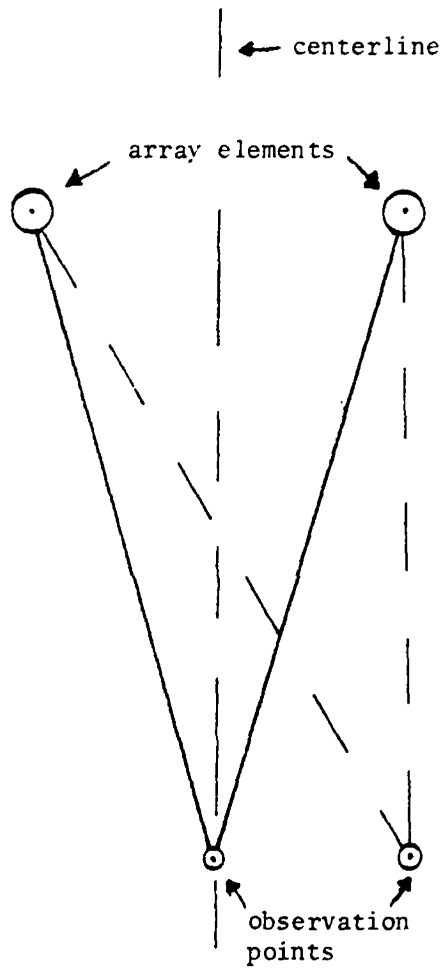
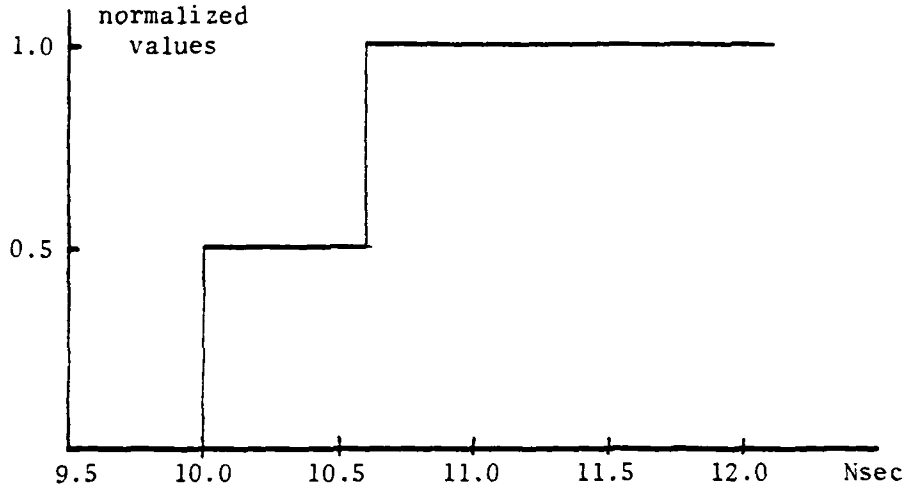
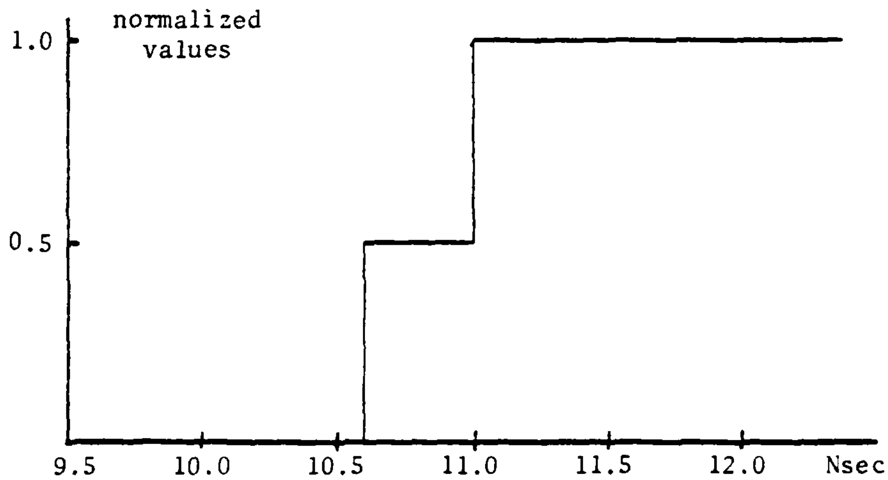


Fig. 3.3. Schematic of two-element array showing effect of shifting observation point.



a. Observation point 3 ft. right of centerline



b. Observation point 5 ft. right of centerline

Fig. 3.4. Theoretical field radiated by a two-element array of long monopoles excited by the ideal step function input voltage, U(t).

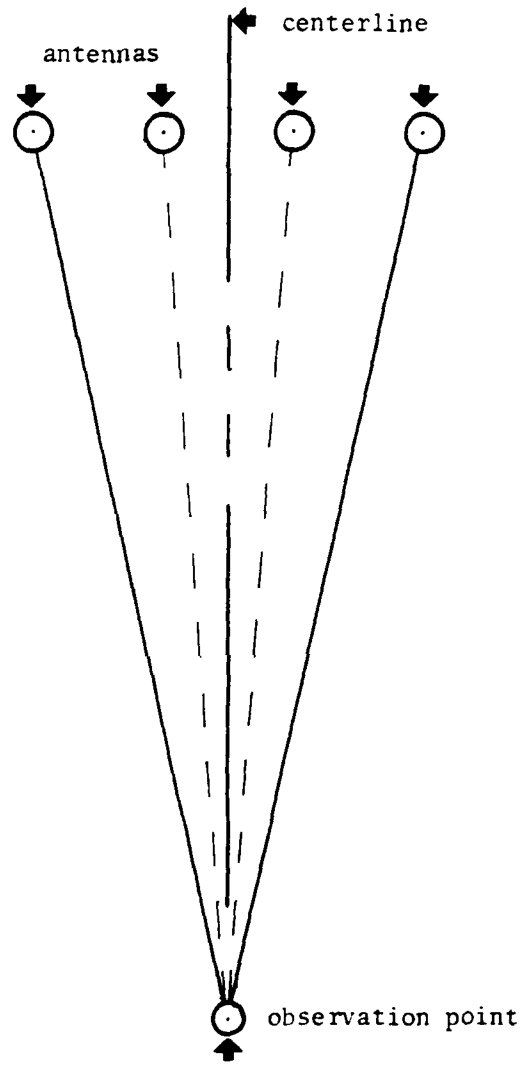


Fig. 3.5. Schematic of four-element array with observation point on centerline.

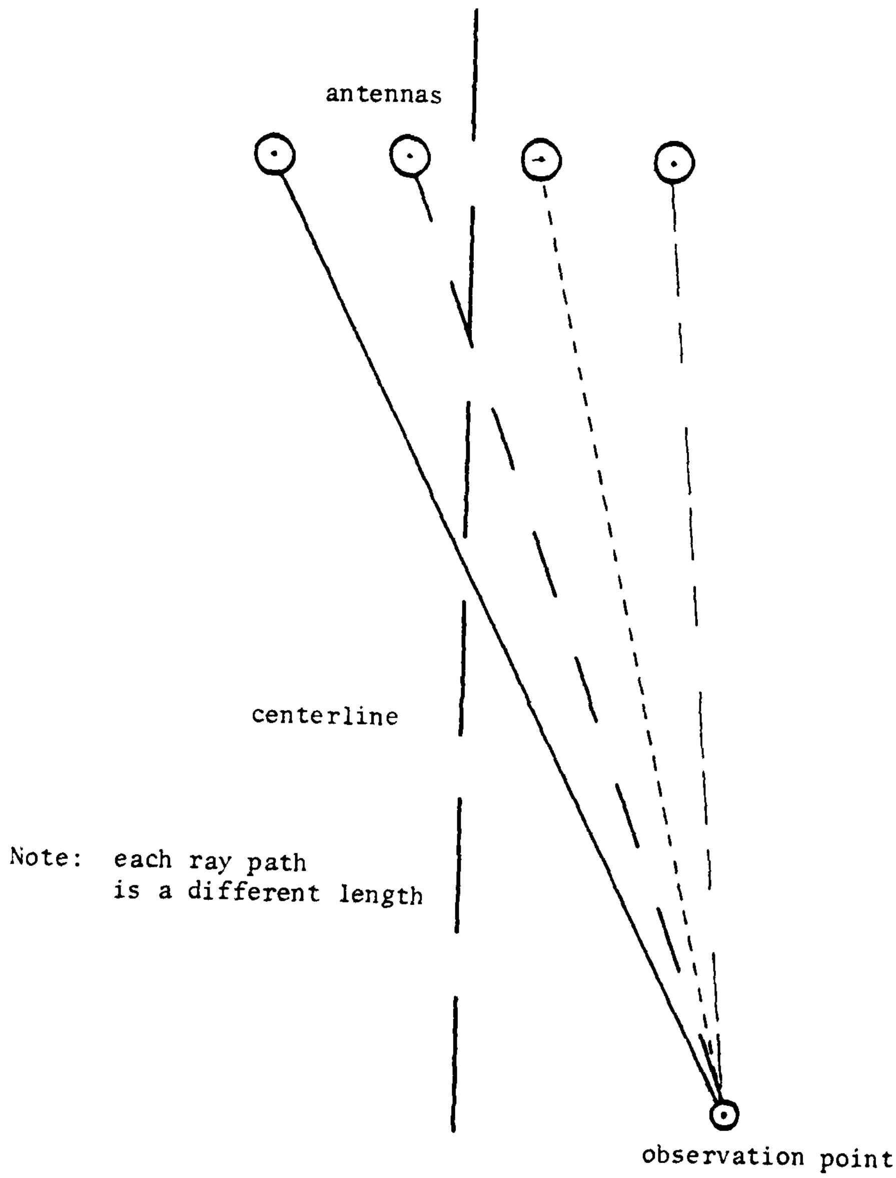


Fig. 3.6. Schematic of four-element array with observation point shifted from centerline.

To aid in analyzing the fields radiated by an array of monopoles, a FORTRAN IV computer program was written to simulate those fields, using the geometry shown in Fig. 3.7.

Description of the Program

A first order approximation was assumed, since only the wave shape was of interest at this time. No attempt to scale the amplitude to predict experimental results was made, nor was the effect of secondary radiation considered. The fields were computed, normalized to the maximum value, and plotted. Program parameters that could be varied were width of the array, number of antennas, the distance between the antennas and a line of observation points (range), and the time scale. For ease of display, plots were shifted by amounts shown on each graph.

If a long monopole is assumed excited by an input voltage, $V(t)$, given by:

$$V(t) = k(1 - \exp(-at))U(t) \tag{3.3}$$

where

k is arbitrary constant,

a is constant, chosen such that rise time closely approximates actual pulse rise time (3.662×10^9),

t is time,

$U(t)$ is the unit step function,

then from Eq. (2.1), the shape of the radiated field $F(t^*)$ from a single monopole at a point P can be expressed by:

$$F(t^*) = \frac{1}{R} V(t^*) \tag{3.4}$$

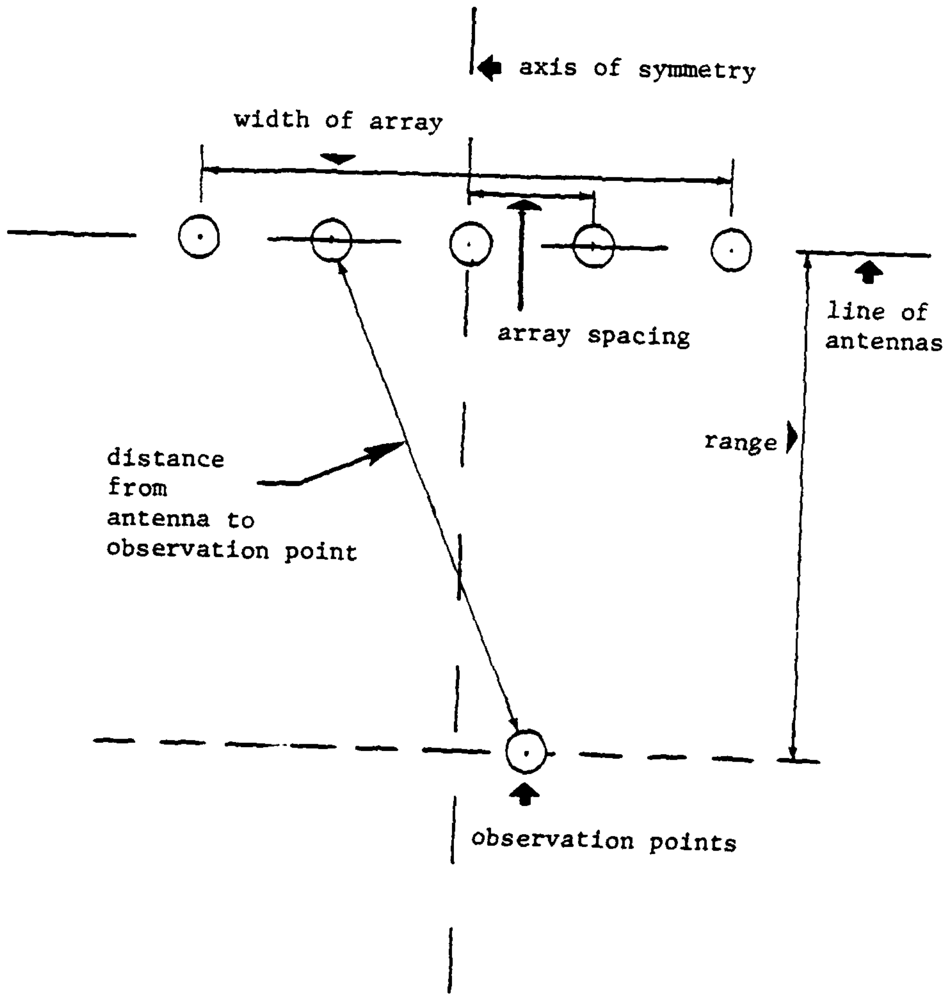


Fig. 3.7. Schematic used for computer simulation program design.

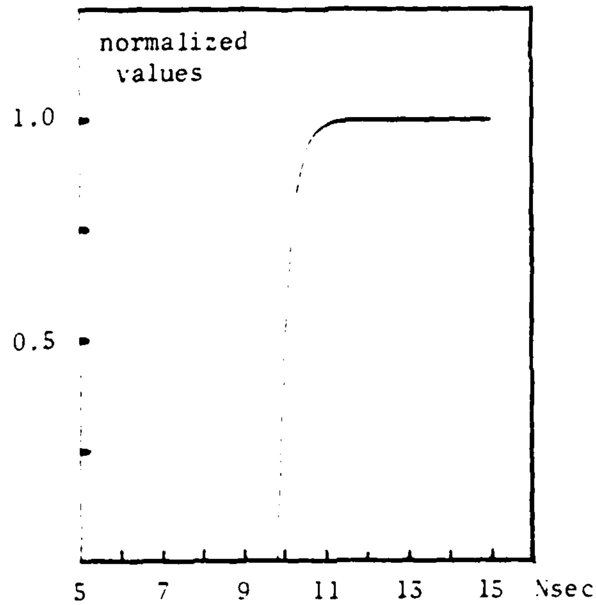
where

> $V(t^*)$ is the input voltage, at the retarded time t^*,
>
> t^* is the retarded time $t - \frac{R}{c}$,
>
> R is the distance from the antenna to the point P,
>
> c is the speed of light.

For the multiple element array, the individual fields are computed using Eqs. (3.3) and (3.4), stored, and then summed algebraically at the point P as its position is shifted away from centerline. Since the array is always centered, symmetry was applied and only positions to the right of center were computed.

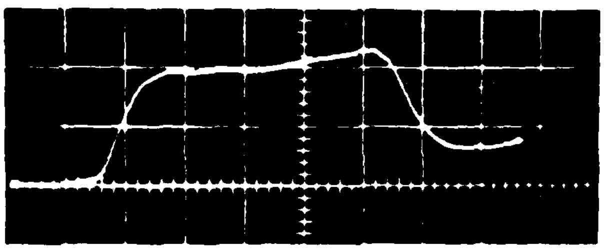
Verifying the Program

After the program was debugged, a simple case for a two-element array with elements spaced two feet apart was run. The predicted stair-step effect was noted as the observation point was shifted off centerline. To confirm these results, a two-element array of long monopoles was constructed and measurements taken. Figure 3.8 compares the experimental results with the simulation plot for the case where the observation point is on centerline. In the simulation, only the leading edge of the pulse was plotted since the trailing edge was assumed symmetrical. For the centerline case, no stair-step effect was noted. Figure 3.9 shows the comparison for a point 3 feet from centerline. The stair-step effect is not clearly shown in the measured data because the integrator response is not fast enough. However, as shown in Fig. 3.10, the stair-step effect is clearly visible. Thus, this first order approximation was confirmed.



a. Computer simulation, leading edge only

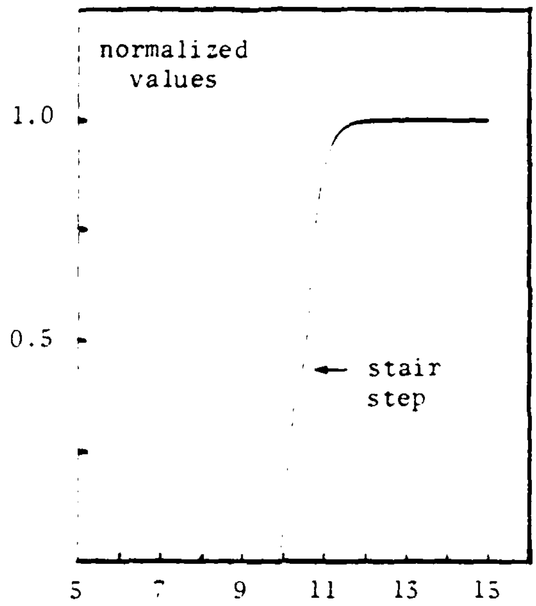
vertical:
50 mV/cm



horizontal: 1 Nsec/cm

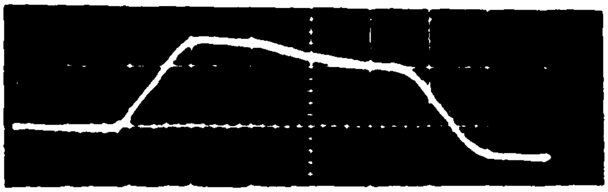
b. Measured probe response, integrated once

Fig. 3.8. Comparison of experimental vs. simulated results of radiated field of a two-element array of long monopoles excited by square wave pulse with finite rise time, probe on centerline.



a. Computer simulation, leading edge only

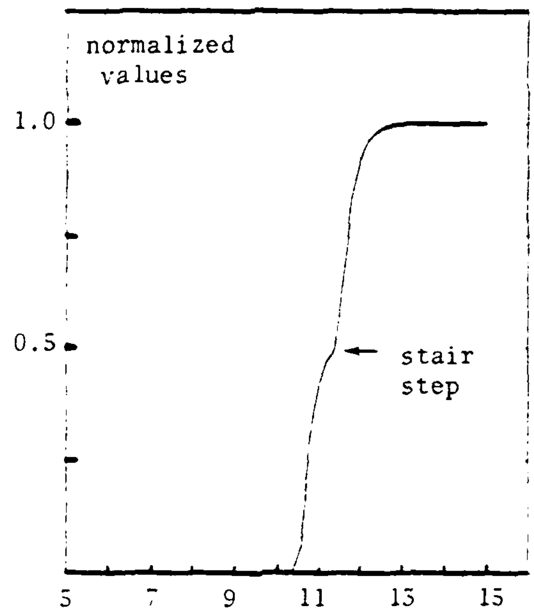
vertical:
50 mV/cm



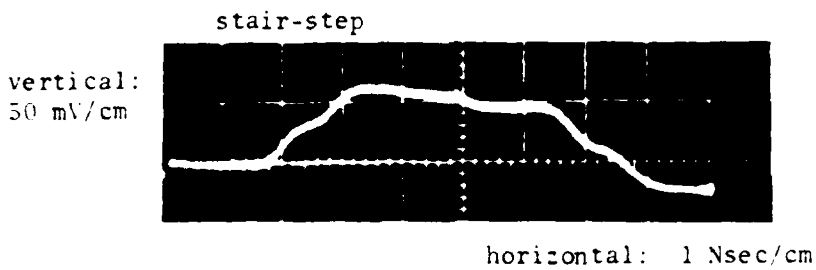
horizontal: 1 Nsec/cm

b. Measured probe response, integrated once

Fig. 3.9. Comparison of experimental vs. simulated results of radiated field of a two-element array of long monopoles excited by square wave pulse with finite rise time, probe 3 ft. right of centerline.



a. Computer simulation, leading edge only



b. Measured probe response, integrated once

Fig. 3.10. Comparison of experimental vs. simulated results of radiated field of a two-element array of long monopoles excited by square wave pulse with finite rise time, probe 5 ft. right of centerline.

Simulation of Larger Arrays

The simulation initially considered cases that could reasonably be expected to be constructed and used on the 28 feet square ground plane. Thus the array widths considered were 10 feet long and 28 feet long with from 1 to 32 antennas. The ranges between the antennas and the observation points selected were 5, 9.6 and 16 feet.

As the data was accumulated, the effect of element spacing became the dominant feature. As the spacing became small, a smoothing of the "stair step" was noted. Figure 3.11 shows a comparison of a 28 feet array with 8 elements (4 feet spacing) and 16 elements (1.867 feet spacing). The smoothing is clearly shown. A special case was run using an ideal step function, U(t), as the input voltage for a 10 feet array with 100 antennas (0.101 feet spacing). Those results showed a very smooth curve (Fig. 3.12). As a result, an expression describing the field, $F_1(t)$, radiated by an array of infinitely close monopoles was derived by Beren (1976, private communication), viz.:

$$F_1(t) = \ln\left[\frac{t + [t^2 - t_o^2]^{1/2}}{t_o}\right] \tag{3.5}$$

where t_o is the time from the plane of the antennas to the plane of observation points, a constant. The derivation assumes an ideal step function input.

When the radiated field represented by Eq. (3.5) was compared against the computer simulation for a case of 500 antennas in a 10 feet wide array (antenna spacing of 0.02 feet), the plots were identical (Fig. 3.13). Equation (3.5) was truncated at a time equal to the time

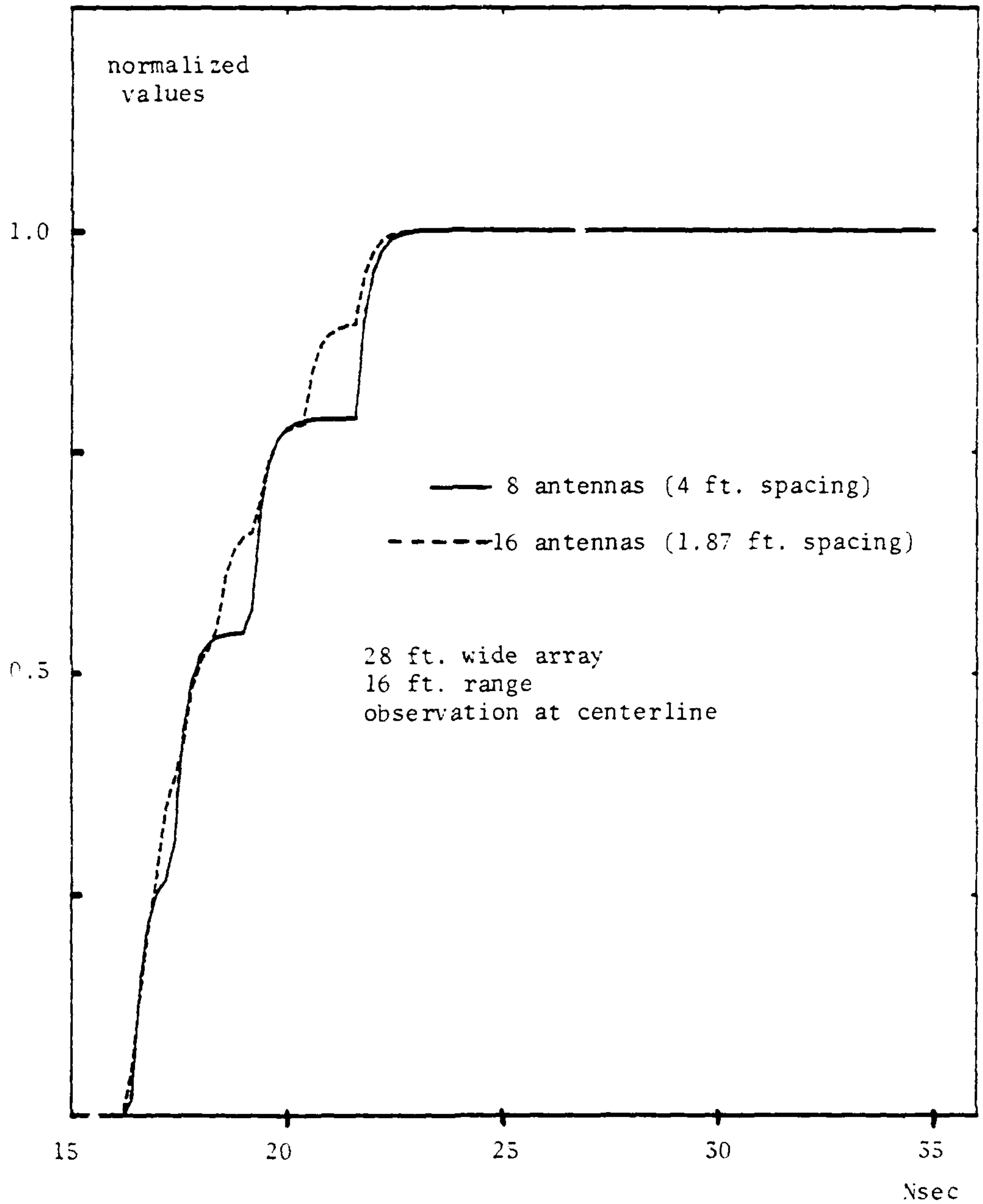


Fig. 3.11. Effect of reduced antenna spacing on smoothness of curve.

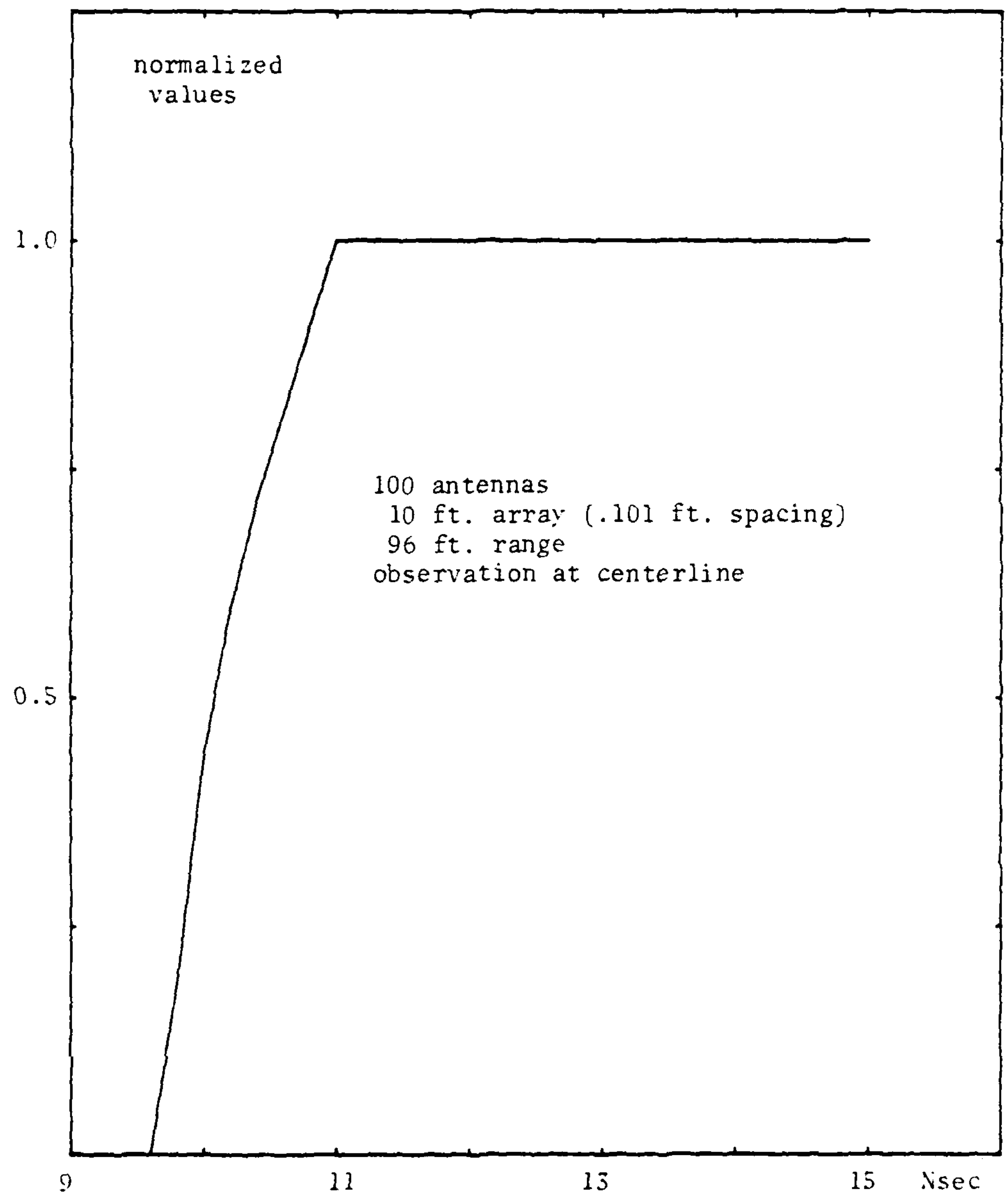


Fig. 3.12. Simulated field, step function input, 0.101 ft. spacing.

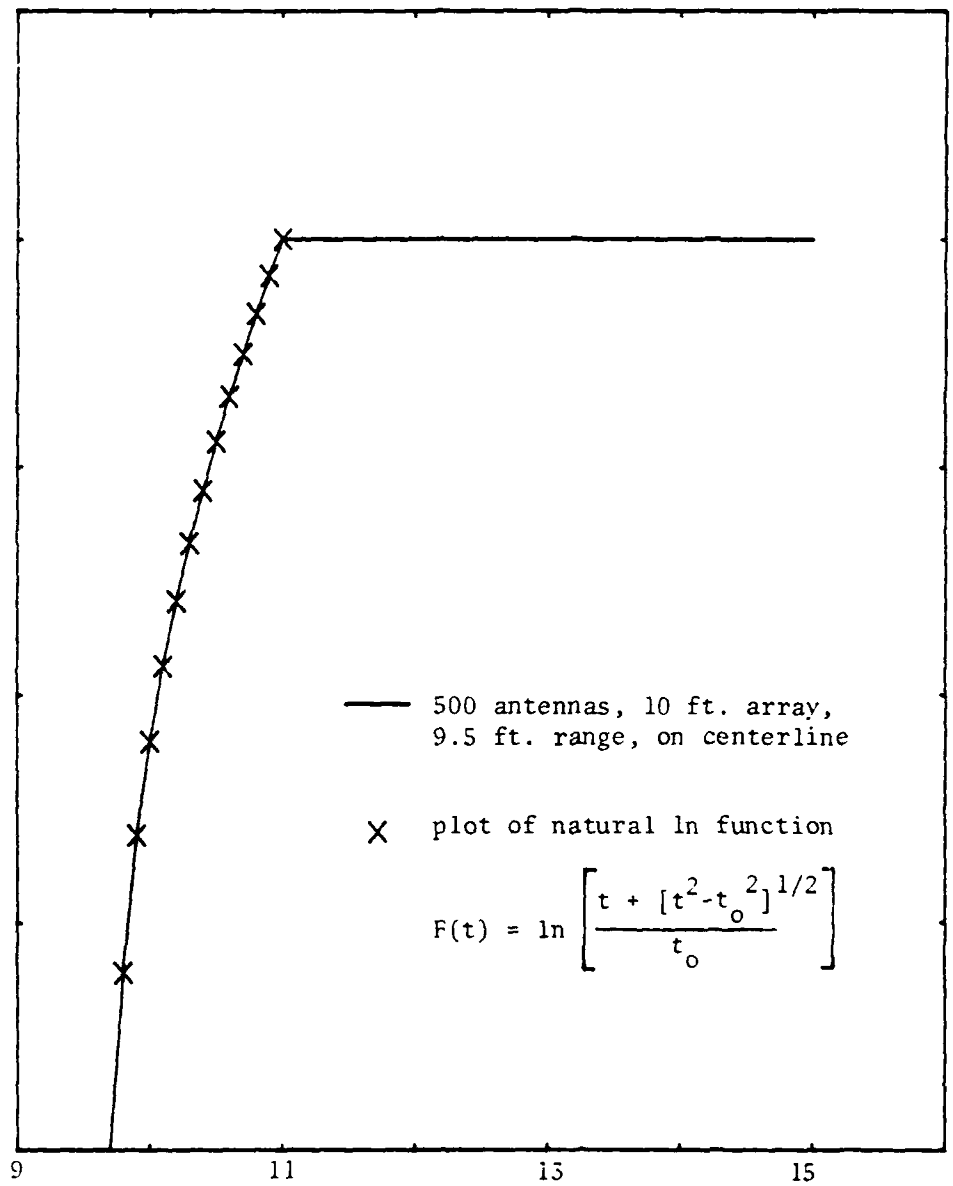


Fig. 3.13. Plot of the natural logarithm function vs. the simulated field of an array with antenna spacing of 0.02 ft.

of arrival of the last pulse from the most distant antenna, as any additional values have no physical meaning.

Another noteworthy effect is shown in Fig. 3.14, which shows the effect of shifting the observation point. When the observation point is shifted to the right, the observed field at that point is identical to the field at the center for a period of time. The amount of time is equal to the time it takes the rightmost pulse to arrive. After that, the field at the shifted position rises slower. That occurs because while the observation position is aligned within the width of the array, the pulses from the individual antennas arrive in pairs except for the one case where an antenna is directly in line with the point (in which case, that pulse arrives before any other pulse). As the observation point is shifted to the extreme edge of the array and beyond, the pulses arrive one at a time. Figure 3.13 shows this effect for a 28 feet array with the observation points at centerline and 5 feet right of centerline.

In summary, for a step function input voltage ((k)(U(t))) to an array of long monopoles, the radiated field at a point distant from the array is constructed from a summation of the fields radiated by the individual elements within the array, with individual field magnitudes determined by the distance traveled. The rise time of the resultant field is directly proportional to the times of arrival of the leading edges of the individual fields. The smoothness of the resultant waveform is related to the antenna spacing, i.e., closer spacing produces smoother curves, assuming the same time scale. As the observation point shifts from the axis of symmetry, the observed field is identical to that at

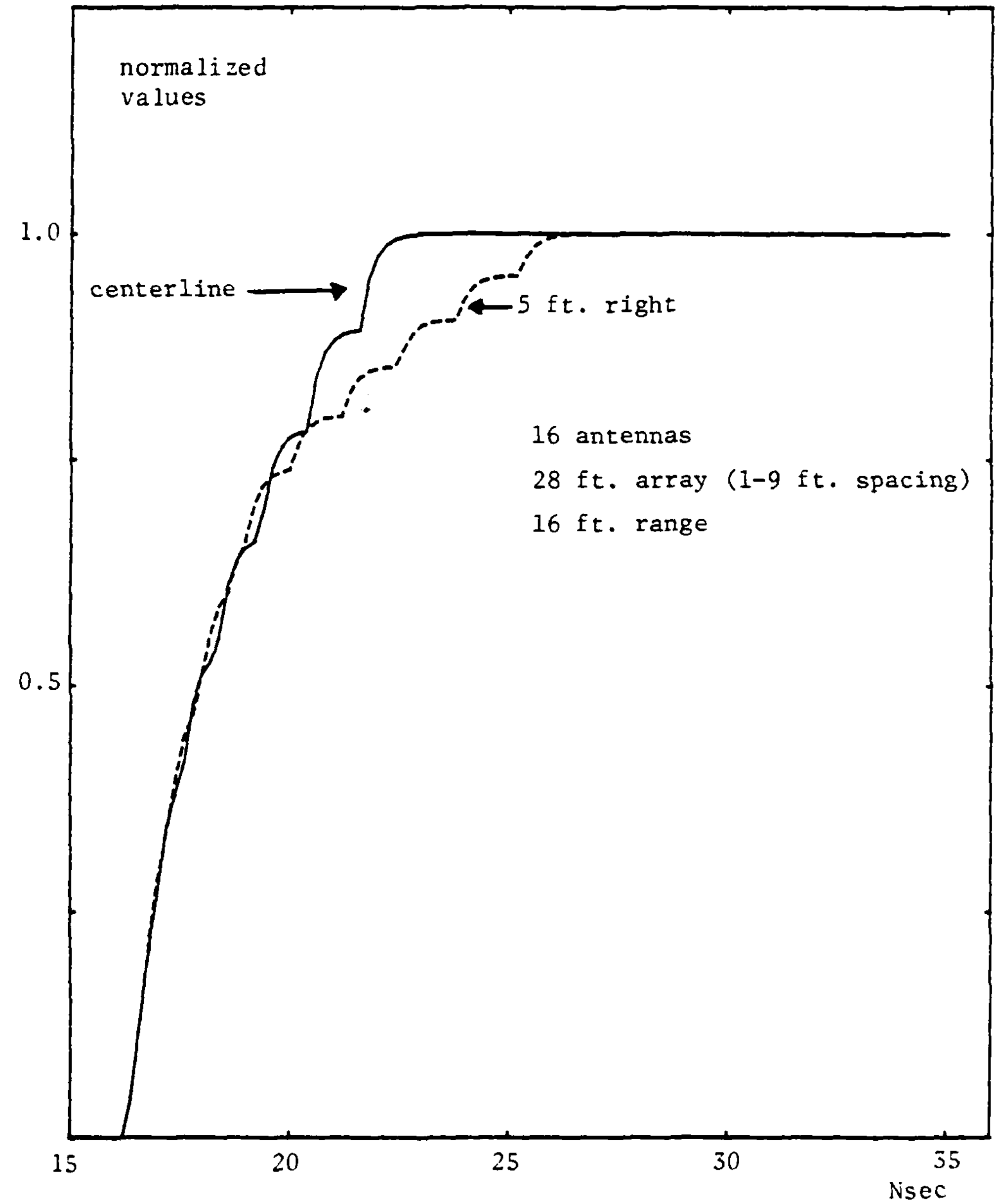


Fig. 3.14. Simulated field at centerline vs. 5 ft. right of centerline.

centerline for a time based on the distance shifted, i.e., the farther right shifted, the sooner divergence from the centerline field occurs. However, the rise time of the resultant field is slower than that of the individual radiated fields.

CHAPTER 4

RESULTS AND CONCLUSIONS

The electromagnetic field radiated from an array of monopole antennas excited by a step function input voltage was shown to be the sum of the individual fields at the observation point. The resultant field had a rise time based on the time of arrival of the individual fields, and a magnitude based on the distance from the array.

A "stair step" effect was predicted and reflected in the data. As the number of array elements was increased, the "stair step" smoothed out and approached a limiting value as the number of elements got very large. The limit was the logarithmic function expressed by Eq. (3.5).

As the observation point was shifted off centerline, the field at the new point was identical to the field at the center for a time related to the distance shifted. Thus, based on the array configuration, a certain amount of planarity was shown.

Conclusions

No practical solution to the rise time degradation caused by the time delay was found. For a number of antennas that one could reasonably expect to construct into an array, 16 to 32 elements over a 28 foot span, the "stair-step" effect was dominant. For those cases where smoothness was shown because of very close element spacing, no conclusion is drawn, since the element spacing is such that secondary

radiation between elements, which was ignored in this simulation, must be considered.

Two approaches to the cylinder illumination experiment could be taken: reduce the experiment scaling such that a single radiating element can be used on the 28 feet square ground plane, or increase the size of the ground plane. Physical constraints precluded the second approach and at the time this study was accomplished, time did not permit a restructuring of the experiment. In either case, the problem should be solved analytically for a dipole antenna as the source of plane waves in order to compare the results. Work performed by Bombart and Libelo which measured the aperture field for the horizontally polarized case should be reviewed for possible application in this experiment (Beren, 1979, private communication).

APPENDIX A

LIST OF EQUIPMENT USED IN THE TEST FACILITY

Unit	Model	Manufacturer
Pulse Generator	Type 109	Tektronix
Readout Oscilloscope*	Type 567	Tektronix
Digital Unit*	Type GR1A	Tektronix
Sampling Sweep*	Type 3T77	Tektronix
Sampling Dual Trace*	Type 3576	Tektronix
Attenuators, 10XT	Type 017-044	Tektronix
Current Transformer	CT-1	Tektronix
Power Supply	HP 715A	Hewlett-Packard
Time Domain Reflectometer	HP 1415A	Hewlett-Packard
Oscilloscope	HP 130B	Hewlett-Packard
Analog Simulator	Model 600	Burr-Brown
Tee, standard	GR 874-T	General Radio
Power Divider	GR 874-TPD	General Radio
Insertion Unit	GR 874-X	General Radio
Tee, 1:100 (Type 874)	Model 960	H-H Research

Note: Units marked * comprise the Sampling Oscilloscope System.

APPENDIX B

CONSTRUCTION AND TEST OF AN ARRAY OF ELECTRICALLY SMALL LOOP ANTENNAS

Building the Antennas

A loop antenna must meet two conditions to be considered electrically small (King, 1969):

1. $a^2 << b^2$
2. $|kb| < 1 \qquad k = \frac{2\pi f}{c}$

where

a = radius of wire

b = radius of loop

c = free space speed of light

f = highest frequency component in pulse

A 3-inch diameter semi-circular antenna was constructed using RG-174 coaxial cable, an Amphenol Subminax connector, and a small brass plate using the design in Fig. B.1. Four 6-inch diameter loops were constructed using Number 14 gage copper wire, Type BNC connectors, and small galvanized plates. See Table B.1 for smallness criteria computations.

Testing the Antennas

Analysis

Franceschetti and Papas (1974) showed that the radiated far field of a small loop antenna was proportional to the first derivative of the

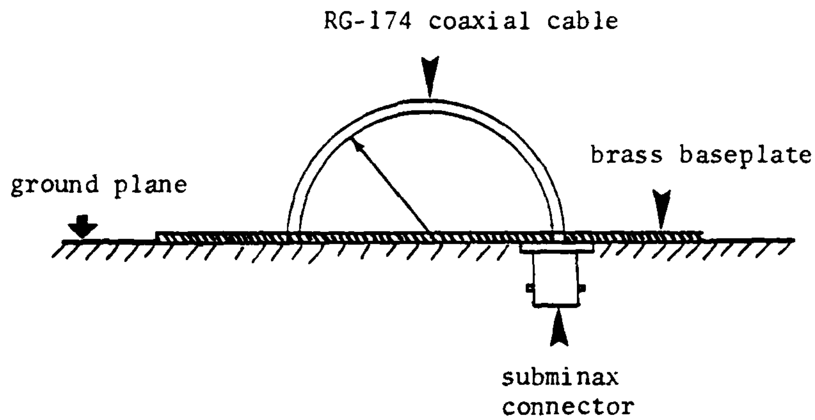


Fig. B.1. Design for semi-circular loop antenna.

Table B.1. Computations used to show that loop antennas used were electrically small.

Loop Diameter (inches)	Wire Radius (inches) "a"	Loop Radius (inches) "b"	$(a)^2$	$(b)^2$	kb
3.0	0.019	1.5	$3.6\text{x}10^{-4}$	2.25	0.625
5.0	0.019	2.5	$3.6\text{x}10^{-4}$	6.25	1.04
6.0	0.051	3.0	$2.6\text{x}10^{-3}$	9.0	1.25

$$kb = \left[\frac{2\pi f}{c}\right]\left[\frac{b}{12}\right]$$

where: $f = 783\text{x}10^{6}$ Hz

$c = 9.843\text{x}10^{8}$ ft/sec

input voltage. Harrison (1964) had previously shown that the load voltage of a small loop antenna, in reception, is proportional to the first derivative of the incident field. Thus, for the configuration shown in Fig. 2.1, the load voltage of the field probe was predicted to be proportional to the second derivative of the input voltage.

For a single radiating loop antenna placed on the ground plane centerline, a time delay is expected as the field probe is shifted either side of centerline. The purpose of the tests was to determine whether some configuration of an array would cause the fields to combine with sufficient planarity to be effective for the desired experiment. One, two, three, and four element arrays were to be tested.

Results and Conclusions

Initially, the 3-inch diameter loop was used to transmit to a 3-inch diameter probe. When placed 9 feet apart, no measurable response was noted. When the probe was placed 4 feet from the transmitting antenna, a moderate response was noted. As a result, it was decided to construct the 6-inch diameter loops and increase the probe diameter to 5 inches. A diameter of 6 inches was the largest the loops could be sized and still be considered reasonably close to an electrically small loop.

In order to maximize the power delivered to the array, the sampling oscilloscope was triggered by an 8-inch monopole placed 4 feet behind the array and the E-H tee was removed. Before beginning the data run, the single antenna was tested using the E-H tee and the 8-inch monopole for triggering, and produced identical results.

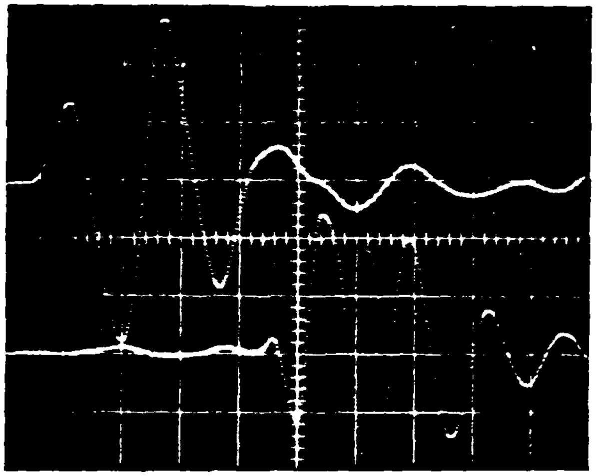
The antennas were oriented with the feed and facing away from the probe, and for the multiple antenna cases, were spaced one foot apart. The array was always centered on the centerline of the ground plane. A complete set of data was recorded as the probe was shifted to the right in one-foot increments. However, only representative data are shown in Figs. B.2, B.3, B.4, and B.5. Although considerable ringing is present, the second derivative nature of the response is clearly evident as well as the distortion caused by the time delay. (The pulses could not be integrated because the Analog Simulator proved defective, and before it was repaired, the decision was made to proceed with the approach described in Chapter 3.)

Building even larger antennas was considered to both solve the ringing problem and increase the amplitude of the pulses. However, based on results published by Dion (1970) which showed that for a large square loop, the transmitted pulse began to approach that transmitted by a long monopole, the decision was made to continue the investigation by analyzing an array of long monopoles, using the results reported by Schmitt, Harrison, and Williams (1966). If a solution could be developed for the monopole case, then perhaps it could be related back to the loop case.

vertical:

200 mV/cm

50 mV/cm



monopole
trigger

probe

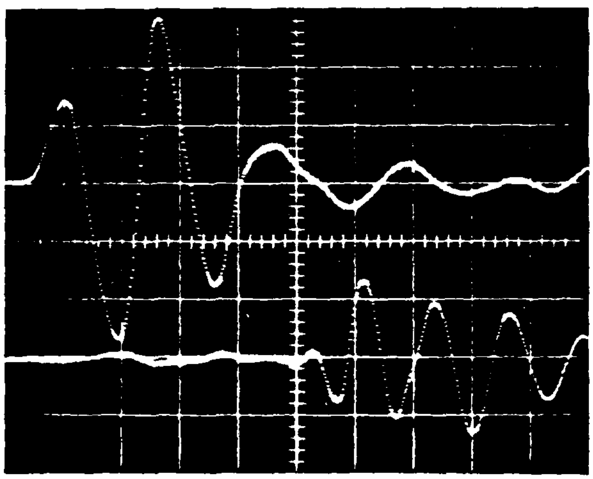
horizontal: 1 Nsec/cm

a. Probe on centerline

vertical:

200 mV/cm

50 mV/cm



monopole
trigger

probe

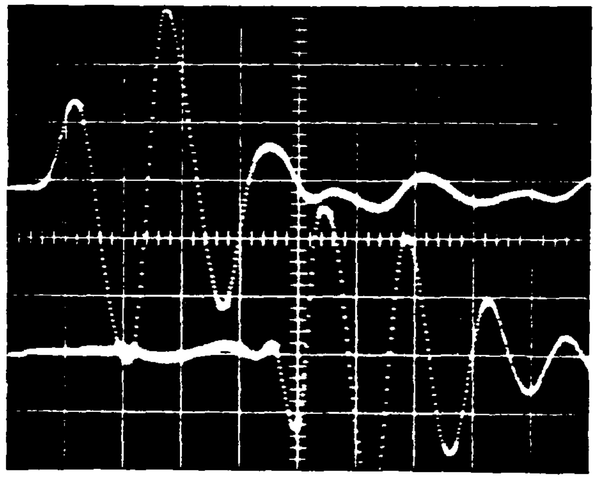
b. Probe 5 ft. right of centerline

Fig. B.2. Load voltages of small loop probe in response to field radiated by single small loop antenna excited by a step function input pulse with finite rise-time.

vertical

200 mV/cm

50 mV/cm



monopole
trigger

probe

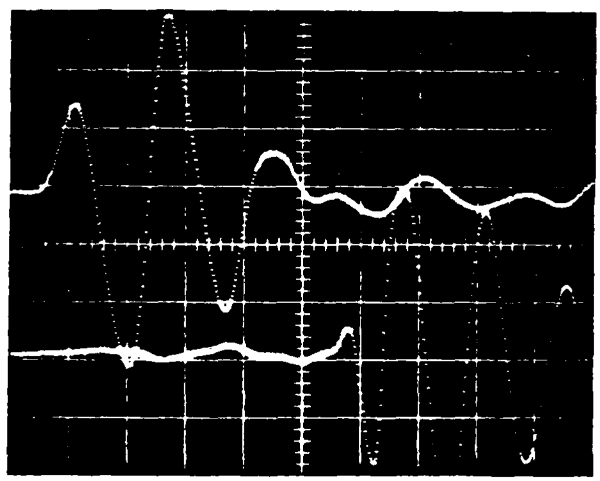
horizontal: 1 Nsec/cm

a. Probe on centerline

vertical

200 mV/cm

50 mV/cm



monopole
trigger

probe

horizontal: 1 Nsec/cm

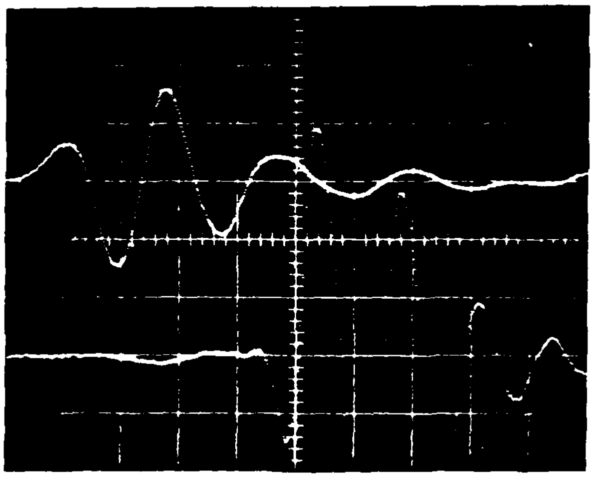
b. Probe 5 ft. right of centerline

Fig. B.3. Load voltage of a small loop probe in response to fields radiated by a two-element array of small loop antennas excited by a step function input pulse with finite rise time.

vertical:

200 mV/cm

50 mV/cm



monopole trigger

probe

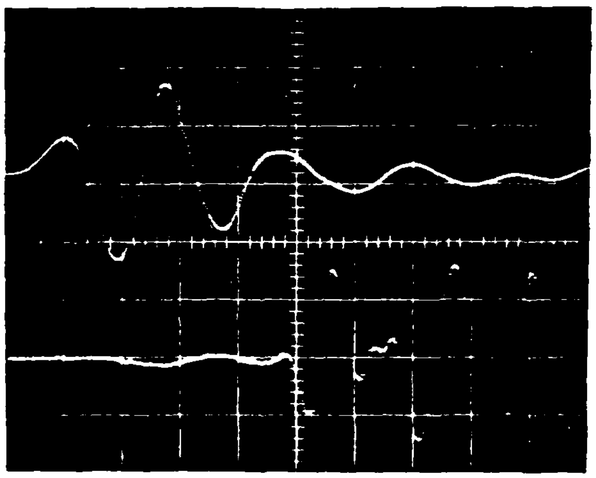
horizontal: 1 Nsec/cm

a. Probe on centerline

vertical:

200 mV/cm

50 mV/cm



monopole trigger

probe

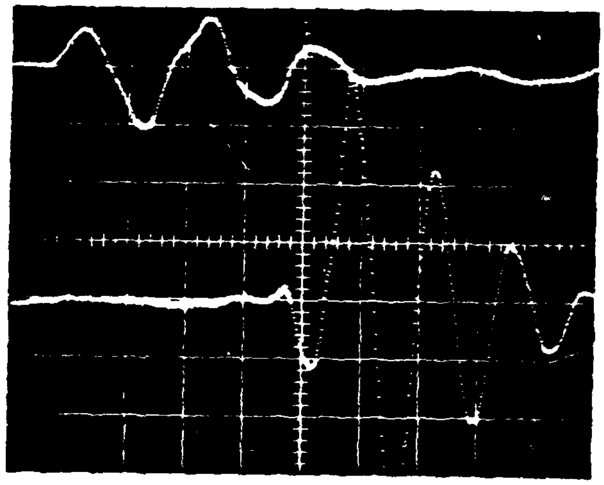
horizontal: 1 Nsec/cm

b. Probe 5 ft. right of centerline

Fig. B.4. Load voltage of a small loop probe in response to fields radiated by a three-element array of small loop antennas excited by a step function input pulse with finite rise time.

vertical:
200 mV/cm

50 mV/cm



monopole
trigger

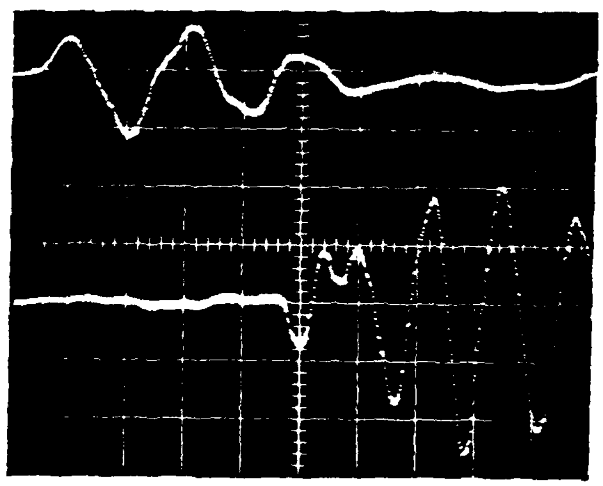
probe

horizontal: 1 Nsec/cm

a. Probe on centerline

vertical:
200 mV/cm

50 mV/cm



monopole
trigger

probe

horizontal: 1 Nsec/cm

b. Probe 5 ft. right of centerline

Fig. B.5. Load voltage of a small loop probe in response to fields radiated by a four-element array of small loop antennas excited by a step function input pulse with finite rise time.

APPENDIX C

COMPUTER SIMULATION OF AN ARRAY OF LONG MONOPOLE ANTENNAS

PROGRAM FIELD   73/73   OPT=0   TRACE   FTN 4.3+P393

```
      PROGRAM FIELD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      INTEGER TIMEDIV
      REAL VAL(300,5),F(300,5)
      REAL R(700),T(700),TPW(700),PT(30),DIST(5)
      DATA R,T,TPW/700*0.,700*0.,700*0./
      DATA F/1500*0./
      DATA SCALE/.5/
      DATA VAL/1500*0./
      DATA PT,DIST/30*0.,5*0./
      DATA ALPHA/3.662E9/
      DATA S/984251968.5/
      DATA TAU/50./
      DATA M/2/
      DATA NCASE/1/
      DATA NPT/6/
      DATA TIMEDIV/60/
      DATA RANGE,SHIFT/7.,6./
      TNOT = RANGE / S
      TNOTSQ = TNOT * TNOT
      TEM = 0.
      C = RANGE * RANGE
      READ 400, IDATE
  400 FORMAT (I2)
      DO 10 I = 1,NPT
   10 READ 500,PT(I)
  500 FORMAT (F5.2)
      DO 12 I = 1,NCASE
   12 READ 600, DIST(I)
  600 FORMAT (F10.2)
    1 READ 700, NANT
  700 FORMAT (I5)
      JK = 2
      A = 10./NANT
      ACTINP = A
      IF(EOF(5))11,2
    2 DO 22 NC = 1,NCASE
         DO 20 I = 1,NPT
      NN = NANT - 1
      IF(NANT.EQ.1)13,14
   14 ASPACE = DIST(NC) / NN
      HAFSPAS = ASPACE / 2.
      GO TO 15
   13 ASPACE = 0.
      HAFSPAS = 0.
   15       DO 30  J = 1,NANT
      R(J)= SQRT(C + (PT(I) +NN* HAFSPAS)**2)
      T(J) = R(J) / S

            DO 40 L = 1,TIMEDIV
      T1 = (L-1) * SCALE * 1.E-9 + SHIFT * 1.E-9
      IF(PT(I).GT.0.)GO TO 16
      IF(T1.LT.TNOT)VAL(L,1) = 0.
      IF(T1.GE.TNOT)VAL(L,1)=ALOG((T1+SQRT(T1*T1-TNOTSQ))/TNOT)
      IF(T1.GT.T(1))VAL(L,1)=ALOG((T(1)+SQRT(T(1)*T(1)-TNOTSQ))/TNOT)
      TEM = AMAX1(VAL(L,1),TEM)
   16 IF(T1.LT.T(J))F(L,JK) = 0.
      IF(T1.GE.T(J))F(L,JK) = ACTINP / R(J)
```

```
      VAL(L,JK) = VAL(L,JK) + F(L,JK)
   40 CONTINUE
      NN = NN - 2
   30 CONTINUE
      TNORM = 0.
      IF(PT(I).NE.0.) GO TO 45
      TNT = 100. / TEM
      DO 51 MP = 1,TIMEDIV
   51 TNORM = AMAX1(VAL(MP,2),TNORM)
      TEMP = 100./TNORM
   45 TEM = 0.
      DO 60 MP = 1,TIMEDIV
      TEM = AMAX1(VAL(MP,JK),TEM)
      IF(PT(I).NE.0.) TNT = 1.
      VAL(MP,1) = VAL(MP,1) * TNT
   60 VAL(MP,JK) = VAL(MP,JK) * TEMP
      PRINT 5000, NANT,IDATE
 5000 FORMAT (1H1,45X,5H*****,*THERE ARE*,I6,2X*ANTENNAS*,5H*****,25X,*D
     1ATE-- FEB*,I3//)
      PRINT 5100, DIST(NC),PT(I),ASPACE,RANGE,TAU
 5100 FORMAT (15X,*WIDTH OF ARRAY*,F7.3,2X,*FEET*,29X,*DISTANCE FROM AXI
     1S OF SYMETRY*,F6.2,2X,*FEET*/14X,*ANTENNA SPACING*,F7.3,2X,*FEET*,
     253X,*RANGE*,F6.2,2X,*FEET*/50X,*PULSE WIDTH*,F5.1,2X,*NANOSECONDS*
     3/)
      PRINT 5200,SCALE,SHIFT,TEM
 5200 FORMAT (15X,*HOR.TIME SCALE*,F6.3,2X,*NSEC. / DIV*,30X,*TIME SHIFT
     1*,F8.3,2X,*NSEC.*//10X,*PLOTS FROM 0.0 TO*,E10.3///)
      CALL MYPLOT(VAL,M,TIMEDIV,100,300,1)
      DO 20 L = 1,TIMEDIV
      VAL(L,JK) = 0.
   20 CONTINUE
      GO TO 1
   11 STOP
       END
```

SUBROUTINE HYPLOT 73/73 OPT=0 TRACE FTN 4.3+P393 02/18/76

```
      SUBROUTINE HYPLOT(Y,M,NF,NS,NSIZ,LTZERO)
      DIMENSION Y(NSIZ,1),LINE(101),L(11),JL(5)
      DATA JL(1), JL(2), JL(3), JL(4), JL(5)
     1                  /1HA,1HB,1HC,1HD,1HE/,JN,JP,JI,JBLANK,JZ/
     11H-,1H+,1HI,1H ,1H$/
      N=0                                                       HUELSMAN
      K=0   $   IF(LTZERO.NE.0) K=1                             HUELSMAN
      DO 101 I=1,11
      L(I)=10*I-110*NS                                          HUELSMAN
  101 CONTINUE                                                  HUELSMAN
      PRINT      105, (L(I), I = 1, 11)                         HUELSMAN
  105 FORMAT (3X,11(I4,6X),6HY(I,1))
      GO TO 115
  110 IF (N/10-(N-1)/10) 125,125,115                            HUELSMAN
  115 ND=0                                                      HUELSMAN
      DO 120 I=1,10                                             HUELSMAN
      ND=ND+1                                                   HUELSMAN
      LINE(ND)=JP                                               HUELSMAN
      DO 120 J=1,9                                              HUELSMAN
      ND=ND+1                                                   HUELSMAN
  120 LINE(ND)=JN                                               HUELSMAN
      LINE(101)=JP                                              HUELSMAN
      IF (N) 135,122,135                                        HUELSMAN
  122 IF(LTZERO)  135,121,135
  121 PRINT      170, N, LINE
      GO TO 195
  125 DO 130 I=1,101,10                                         HUELSMAN
      LINE(I)=JI                                                HUELSMAN
  130 CONTINUE                                                  HUELSMAN
  135 DO 160 I=1,M                                              HUELSMAN
      XNS=NS                                                    HUELSMAN
      JA=Y(K,I)+101.49999-XNS                                   HUELSMAN
      IF (JA-101) 140,155,145
  140 IF (JA) 150,150,155                                       HUELSMAN
  145 LINE(101)=JZ                                              HUELSMAN
      GO TO 160                                                 HUELSMAN
  150 LINE(1)=JZ                                                HUELSMAN
      GO TO 160                                                 HUELSMAN
  155 LINE(JA)=JL(I)                                            HUELSMAN
  160 CONTINUE                                                  HUELSMAN
      IF (N/10-(N-1)/10) 175,175,165                            HUELSMAN
  165 PRINT      170, N, LINE, Y(K,1)                           HUELSMAN
  170 FORMAT (1X,I4,101A1,1X,  E12.5)
      GO TO 185                                                 HUELSMAN
  175 PRINT      180, LINE, Y(K,1)                              HUELSMAN
  180 FORMAT (5X,101A1,1X,E12.5)
  185 DO 190 I=1,101                                            HUELSMAN
      LINE(I)=JBLANK                                            HUELSMAN
  190 CONTINUE                                                  HUELSMAN
  195 N=N+1                                                     HUELSMAN
      K=K+1                                                     HUELSMAN
      IF (K-NF) 110,110,200
  200 RETURN
      END                                                       HUELSMAN
                                                                HUELSMAN
```

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